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# Long-term Flow Dynamics of Three Experimental Forested Watersheds

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***Abstract.*** Three 1st, 2nd, and 3rd order experimental forested watersheds located within Francis Marion National Forest in Coastal South Carolina were monitored for rainfall and stream outflows. These watersheds were WS80, a pine-hardwood forest (206 ha); WS79 a predominantly pine forest (500 ha); and WS78, a mixed land use dominated by pine-hardwood forests (5,000 ha). The mean runoff coefficients for the 13-yr period (1964-76) for WS78, for the eight-yr period (1966-73) for WS79, and for the eight-yr period (1969-76) for WS80 were 38%, 25%, and 21%, respectively. However, when the same five-year period (1969-73) was considered for all watersheds, the mean runoff coefficients for WS78, WS79, and WS80 were 44%, 27% and 22%, respectively. The largest watershed consistently yielded higher annual water yields compared to the two other smaller ones. Flow duration curves were derived to examine the exceedance probabilities of daily stream flow regimes on each of the watersheds. The flow frequency analysis with 13, 7 and 13 years of peak flows for WS78, WS79 and WS80, respectively, employing Pearson III-type distribution revealed the peak flows for 100-, 50-, 25-, 10-, and 5-year return periods as 1805, 1565, 1326, 1009, and 769 cfs for WS78, 379, 325, 272, 200, and 146 cfs for WS79, and 73, 63, 54, 41, and 32 cfs for WS80. These results are in good agreement with data calculated using USGS developed formulae for the South Carolina Lower Coastal Plain. These results have implications in design of engineering structures, water and nutrient management as well as in evaluation of impacts of development and natural disturbances on the forested lands of the Atlantic Coastal Plain.

**Keywords.** Stream outflow, Runoff coefficient, Peak flows, Flow-frequency-duration, Pine forest.

## Introduction

Scientists recognize that long-term hydrologic monitoring of watersheds is necessary if they are to understand the basic physical processes governing the dynamics of stream flow, storm events, and their interactions with other hydrologic components such as precipitation, evapotanspiration (ET) and ground water flow (seepage). Furthermore, long-term monitoring provides baseline data for assessing the impacts of natural and anthropogenic disturbance on these processes, conservation of regional ecosystems, generation of scientific hypotheses, and testing of hydrologic and water quality models (Amatya et al. 2005).

Generally the long-term hydrological observations on a watershed include precipitation, stream water level, flow rate (discharge) and velocity and ground water level. These observations are essential components for characterization of watershed hydrology, water budgets, rainfall-runoff relationships, water and water resources management, design of hydraulic structures, and the management of eco-hydrology (water quality, vegetation and aquatic habitat). Stream flow dynamics of a watershed is generally characterized by spatial and temporal distribution of varying flow regimes. The parameters describing the flow dynamics are runoff ratios, maximum peak flow rates, low flow rates, and their temporal distribution, flow frequency and duration and storm event characteristics. The dynamics of stream flow may be impacted by changes in land use, climate and other natural and anthropogenic disturbances.

In recent years, land use changes due to timber management and increasing urban development in the Southeastern U.S., especially in the forested lands of the Atlantic Coastal Plain, have led to studies on the hydrology, water quality and effective management of Southeastern forested ecosystems (Harder, 2004). This landscape is characterized by low-gradient poorly drained soils, where stream flow processes are regulated predominantly by shallow water table positions. In order to address the impacts of forest management (such as harvesting, thinning, prescribed burning etc.) on stream flow (runoff), soil moisture, and flooding on these coastal plain landscapes, the USDA Forest Service Southeastern Forest Experiment Station (since renamed as the Center for Forested Wetlands Research (CFWR)) in Charleston, SC had established four experimental watersheds of various sizes (WS 77- 160 ha, WS 78 – 5000 ha, WS 79 – 500 ha, and WS 80 – 200 ha) within the Francis Marion National Forest (Fig. 1) during the 1960's (Amatya and Trettin, 2005). Various eco-hydrologic studies were conducted by collecting data from these watersheds. Young (1966) reported a two-year water budget for the treatment watershed (WS 77) and concluded that excess water in the form of runoff could be problematic in downstream flooding, and that there was no dependable base flow generated from this natural watershed. Young (1967) also described the flooding pattern, flashiness, and effects of storage on these forested lands in controlling the outflow processes. Data on hydrology, stream flow, water budgets and water quality for the periods from 1967 to 1979 (pre-Hugo) and 1990 to 2001 (post-Hugo) have been published elsewhere (Binstock, 1978; Richter et al., 1983; Sun et al., 2000; Miwa et al., 2003; Amatya et al, 2003). Data from watersheds WS 78 and WS 79 (Fig. 1) have not been previously reported.

The main objectives of this paper are three-fold: (1) to quantify the runoff-rainfall relationships, (2) to derive the flow duration curves and (3) to estimate the magnitude and frequency of maximum floods and minimum discharges using the historical data measured between 1964 and 1976 on three 1$^{st}$, 2$^{nd}$, and 3$^{rd}$ order forested watersheds. Statistical tools are used on these long-term hydrological observations to provide a basis for meaningful interpretations of sustainable forest management and decision-making processes for water quantity and quality, including design of water management structures.

## Methods

### *Site Description*

Watershed WS 80: The watershed, first delineated in 1968, drains a first-order headwater stream and is contained within the Santee Experimental Forest near Huger, SC. This site serves as the control watershed for a paired watershed system that includes a treatment watershed (WS77) (Young and Klaiwitter, 1968; Harder, 2004). WS80 is 200 ha in size and has not been managed for over eighty years. The first order stream flows into Fox Gulley Creek (WS 79), then into Turkey Creek (WS 78), a tributary of Huger Creek, which drains ultimately into the Cooper River, an estuarine river of the Atlantic Ocean. The total length of the perennial stream is 1375 m and the relief at the site is about 6 m. After Hurricane Hugo in 1989, natural regeneration resulted in three general forest canopy types: pine hardwood (39%), hardwood pine (28%) and mixed hardwoods (33%). The study site consists of primarily moderately drained sandy loam soils with poorly drained clayey subsoils of the Wahee-Lenoir- Duplin association (Harder, 2004).

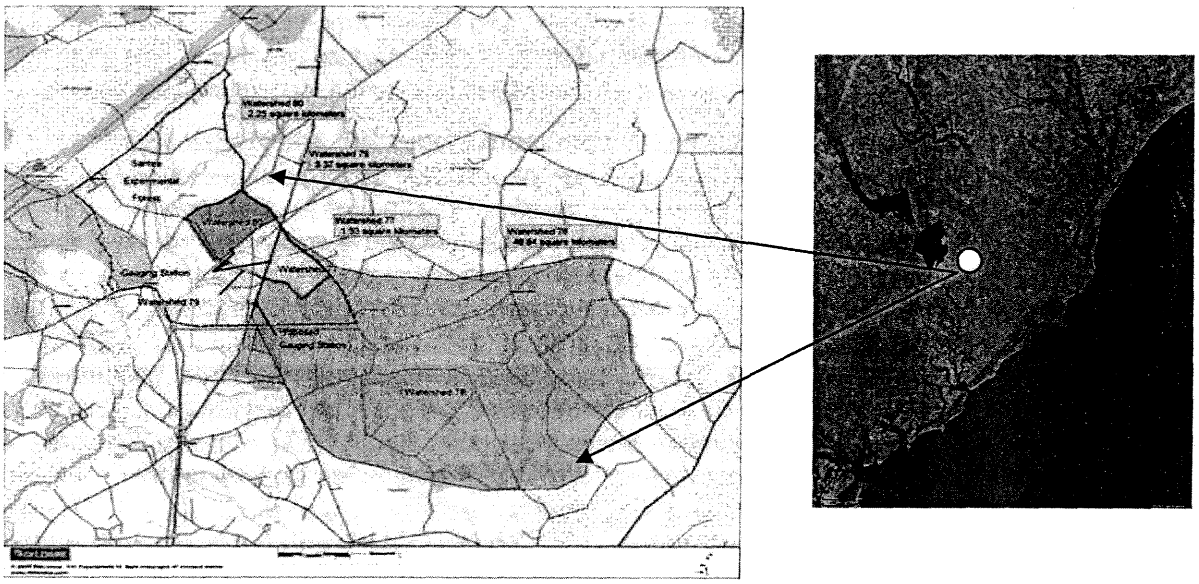

Figure 1. Location map of three experimental watersheds (WS 78, WS 79, and WS 80) at the Santee Experimental Forest (left) in Coastal South Carolina (right).

Watershed WS 79: This is a second-order watershed with 1640 m long stream channel draining Fox Gulley Creek, which contains both watersheds WS77 and WS80 as well as a part between them (Fig. 1). The watershed with a drainage area of approximately 500 ha is located within the Santee Experimental Forest. The soils in this watershed (Lenoir, Meggett, Duplin and Craven) all are clays ranging from poorly to moderately well drained. The impressive size of the relict (pre-Hugo) pines and hardwoods as well as the rapid growth of the post-Hugo natural regeneration (pine and hardwood) attest to high productivity of the soils (Dupre, 2005, Personal communications). The elevations at the site vary from 3 m to 10 m a.m.s.l .

Watershed WS 78: The third-order watershed (also called Turkey Creek) with a stream channel length of 11.4 km over a relief of 3 to 12 m a.m.s.l. draining approximately 5000 ha of the Francis-Marion National Forest (Fig. 1). Land use within the watershed comprises of 52% forest (mostly regenerated loblolly and long leaf pine within Francis-Marion National Forest), 28% wet shrubs and scrubs, 14% wetlands and water with the remaining 6% developed for agricultural lands, roads and open areas. The forest area was almost completely damaged by Hurricane Hugo in September 1989. The watershed is dominated by poorly drained clayey soils of Lenoir-Lynchburg series followed by some sandy and loamy soils.

### *Hydrologic Measurements*

#### Rainfall

Rainfall was measured using a manual gauge at the weather station located within the Santee Experimental Forest Headquarters, which is about 2 km from the watershed WS 80 (Fig. 1). The weather station comprising of a rain gauge and temperature recorder installed in 1946 was upgraded to an automatic one (Campbell Scientific CR-10X) in 1996. Additional rain gauges have been distributed over the watersheds since 1964; at present there are five gauges.

#### Stream Flows

<u>WS 80:</u> The gauging station at the outlet of this watershed consists of a compound V-notch weir and a flat crested weir installed under the Yellow Jacket Road Bridge, and a gauge house with a stage recorder (Fig. 1). The stage (water level) measured above the bottom of the V-notch weir was used to estimate the flow rate using standard weir equations. Flows on this watershed were monitored from 1968 to1981 and did not start again until after Hurricane Hugo in November 1989. Since then the flow monitoring has been ongoing. Details of the outlet type and methods of flow estimates are given elsewhere (Young 1967; Harder 2004).

<u>WS 79:</u> The outlet of this second-order watershed comprises of a compound V-notch weir in the middle with two rectangular concrete box culverts on either side. The bottom of the culverts are flushed with the top of the V-notch weir allowing to measure large outflows through the culverts after the V-notch weir is full. The outlet structure is located under the bridge of Lotti Road, a boundary of the watershed (Fig. 1). The gauge house is located on the left bank. Stage levels on this watershed were monitored between 1966 and 1973 and did not start again until 1996. Stage-discharge rating curves were developed to estimate the flow rates using the stage data.

<u>WS 78:</u> The original outlet for the gauging station on this watershed was located about 800m downstream of the existing Turkey Creek Bridge on Highway 41 N near the town of Huger, SC. The abandoned outlet comprising of a gauge house on the left bank and the openings at various levels of an embankment measured stages of the stream from 1964 to 1984 (Young 1965). Stage-discharge rating curves were developed to estimate the stream flow rates. Under a recent cooperative agreement with the Forest Service, Atlanta-based Tetra-Tech, Inc. helped digitize the historical stream flow data recorded on the strip-charts. A new stream gauging station has recently been established slightly upstream of the old abandoned station by the collaboration with USGS and College of Charleston (Amatya and Trettin 2005).

Most of the stage data recorded from 1960s to mid-1990s, until the new electronic data loggers were installed, were on magnetic punch tapes, which were digitized at the USDA Forest Service Coweeta Hydrologic Laboratory in NC. Measured stage elevations were processed with SAS programs to compute flow rates. In this study, stream flow rates only from 1964 to 1976 for all watersheds were integrated into daily watershed depth-based outflows using the corresponding watershed areas for further analyses. Annual runoff-rainfall ratios were computed dividing measured annual stream flow (runoff) by rainfall for each of the watersheds. Flow duration curves for all three watersheds were derived using daily stream flow data. These graphical plots illustrate the percent time flow exceeds or equals a certain value of interest. The slopes of these curves can also be used to characterize the flashiness and base flows.

## *Flood Frequency Analysis*

This analysis was conducted to determine T-years floods and discharges - the discharges that appeared in the research cross-section - with the certain probability of occurrence.

The most common and frequent uses of statistics in hydrology have been that of frequency analysis. The goal of the frequency analysis is to estimate the magnitude of an event having a given frequency of occurrence or to estimate the frequency of occurrence of an event having a given magnitude (Haan 2002). The frequency is often stated in terms of return period, *T*, in years, or a probability of occurrence in any one year, *p*. Hydrologic frequency analysis can be made with or without making any distributional assumption. In the present paper the authors used two different distributional assumptions: the one for maximum floods (Pearson III distribution) and the second for minimum discharges (Gumbel distribution). If a distributional assumption is made, the magnitude of events for various return periods is selected from the theoretical "best-fit" line according to the assumed distribution.

When we do not have hydrological observations for a certain period of time or the adequate long time series, we could use regional formulas to calculate the *T*-years floods (obviously it is possible if such formulae exist for the study region). We also very often do such calculations to compare the results from different methods (in this case having distributional analysis) to obtain a better understanding of flow dynamics of watersheds. In the present paper all methods mentioned above to were used calculate maximum floods and minimum discharges.

### Distribution of extreme discharges from long-term observations

For hydrologic studies and in management of water resources it is often necessary to predict an extreme event, which could be a flood. It is, however, almost impossible to predict with certainty if a flood will occur, say, next year. Instead we try to predict the probability of a flood or the extreme discharge (e.g. minimum). If a flood has occurred 4 times in the last 100 years then we can simply state that there is probably a 1 in 25 chance that one will occur next year. When we have discharges for a period of observations in a particular river/stream site, we analyze all of the data for that period to identify the best-fit line for a given distribution. The fitting is usually done by the computation of parameters of the theoretical curve from observed data.

In this paper we use the Pearson Type-III distribution to determine the maximum extreme flood for the three watersheds studied herein. This method was used for the analysis of maximum events (Chow 1969; Novak 1972; Haan 2002) and the Gumbel extreme value distribution for minimum discharge analysis (Novak 1972; Byczkowski 1972; Wanielista et al. 2003). Although for computational ease the computer model DISTRIB (Wanielista et al. 2003) could have been used, the authors did all statistical calculations using spreadsheets and formulae available in the classical statistics text books (Chow 1969, Novak 1972).

Generally, the Pearson distribution is represented by following probability density function. The mode of this function is x = 0. This equation is a selective case of the three parameter gamma distribution (Wanielista et al. 2003):

$$p_x(x) = p_o\left(1 + \frac{x}{\alpha}\right)^{\alpha/\delta} e^{-x/\delta}$$

where, $\alpha$ = difference between mean ($\mu$) and mode ($\alpha = \mu - X_m$), $X_m$ = mode of population x, $\delta$ = scale parameter of distribution, $p_o$ = value of $p_x(x)$ at mode.

Substituting y = ln (x) for x in the Pearson distribution gives the Log Pearson type-III distribution:

$$p_x(y) = p_{yo}\left(1+\frac{y}{\alpha}\right)^{\alpha/\delta_y} e^{-y/\delta_y}$$

where, $\alpha$ = difference between mean and mode ($\alpha = \mu_y - Y_m$), $Y_m$ = mode of population y, $\delta$ = scale parameter of distribution, $p_{yo}$ = value of $p_x(y)$ at mode.

The Gumbel distribution also referred to as Fisher-Tippett Type I, Double Exponential, Gumbel Type I, and Gumbel Extremal distribution (Byczkowski 1972; Wanielista et al. 2003) is characterized by the probability density function:

$$p_x(x) = \frac{\alpha}{\beta-\gamma}\left\{\frac{x-\gamma}{\beta-\gamma}\right\}^{\alpha-1} e^{-\left\{\frac{x-\gamma}{\beta-\gamma}\right\}^{\alpha}}$$

where, $\beta$ = scale parameter of the distribution, $\gamma$ = location parameter of the distribution.

### Lower Coastal Plain formulae for maximum floods

To provide simple methods of estimating flood peak discharges, the US Geological Survey has developed and published regional formulae for every State including the State of South Carolina. In 1993, the USGS in cooperation with the Federal Emergency Agency and the Federal Highway Administration prepared and compiled all equations from all US to one computer program, entitled the National Frequency Program (USGS 2000). The State of South Carolina was divided into four regions: Blue Ridge, Piedmont, Upper Costal Plain and Lower Costal Plain. All areas were divided into rural and urban. Since the watersheds studied herein which are located in rural areas of the Lower Costal Plain region, following formulas were used to estimate T-year floods (Guimares & Bohan 1992; USGS 2000):

$Q_2 = 56A^{0.63}$; $Q_5 = 111A^{0.61}$; $Q_{10} = 157A^{0.59}$; $Q_{25} = 221A^{0.59}$; $Q_{50} = 275A^{0.58}$; $Q_{100} = 335A^{0.58}$ and $Q_{500}=569A^{0.52}$.

For South Carolina the regression equations were developed from peak discharges monitored through 1988 in 52 stream gauging stations. However, there are some restrictions in application of these formulae (such as the limitation of the area and certain locations within the state) but they are not pertinent to the research area covered in this paper.

## Results and Discussion

### *Runoff-Rainfall Relationships*

WS 80: Computed runoff-rainfall ratios for this 1st order watershed for the period of 1969 to 1976 varied from 16% in 1972 to 29% in 1971 (Fig. 1) for the rainfall of 1106 mm and 1694 mm, respectively. These ratios corresponded to depth-based stream flows of 175 mm in 1971 to 499 mm in 1972. The average ratio was computed to be 21%. There was more variability in annual runoff (Coefficient of Variation, CV = 0.33) compared to the annual rainfall (CV = 0.14) for the same period. The computed runoff-rainfall ratios for this watershed with matured pine and hardwood mixed forest before the impact of Hurricane Hugo are consistent with similar other naturally drained forested watersheds in the coastal plain (Chescheir et al 2003).

WS 79: The maximum and minimum runoff ratios observed during 1966 to 1973 for this second order watershed were 10% in 1968 with 1141 mm of rainfall to 40% in 1966 with 1505 mm of rainfall with an average of 25%. These ratios corresponded to annual runoff of 114 mm and 599 mm. As on WS 80, the runoff was much more variable (CV = 0.54) than the rainfall (CV = 0.17). Although the maximum rainfall measured was 1694 mm in 1971, the runoff coefficient was only 35%. This indicates that the dry antecedent conditions in later part of 1970 (Fig. 2). Although WS 80 is also a part of WS 79, one reason for its higher runoff coefficient compared to WS 80 may be due to various types of disturbances that had occurred on the treatment watershed WS 77 with an area of 160 ha containing within this watershed WS 79.

<u>WS 78:</u> This third-order largest watershed yielded the runoff ratios ranging from 17% in 1968 with a rainfall amount of 1141 mm to as much as 58% in 1971 with an annual rainfall of 1694 mm with an average of 38% for the 13-year (1964-76) period (Fig. 2). Again the computed CV of 0.45 for the runoff was much higher than the CV of 0.18 for the measured rainfall. Note that the CV for the rainfall for this 5,000 ha watershed was computed using data from only one gauge. Rainfall in this region has been reported to have a large spatial variability, especially during summer tropical storms (Richter et al., 1983; Harder, 2004; Amatya et al. 2002).

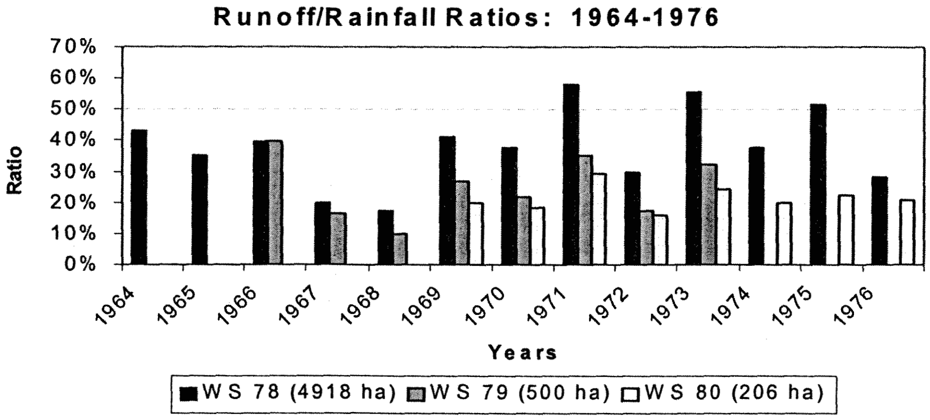


Figure 2. Annual runoff ratio as a percentage of rainfall for three experimental watersheds.

When the runoff ratios were compared across the same 5-year period (1969-1973) (Fig. 2), WS 78, the largest watershed consistently yielded the highest values (average = 44%) followed by the second largest WS 79 (average = 27%) and the smallest WS 80 (average = 22%). However, the difference between WS 79 and WS 80 were much smaller compared to the difference between WS 78 and WS 79. Again this 5% increased runoff depth may be explained by some treatments done on part (WS 77) of WS 79. Interestingly, the CV for annual outflows was nearly the same (0.40) for all three watersheds compared to that of 0.16 for the rainfall.

Daily cumulative stream flow dynamics for these three watersheds are compared for the same five-year period in Fig. 3. Clearly the daily cumulative flow indicated the least response (lower runoff) to rainfall for the smallest watershed (WS 80) compared to the other two larger watersheds. The total cumulative outflow of 1802 mm from the watershed WS 79 for the five-year period was only 20% higher than the total of 1506 mm for the smallest watershed WS 80, perhaps for the same reason stated earlier. However, the result for the largest watershed (WS 78) yielding double the total outflow of WS 80 is somewhat speculative and possibly may be an overestimate.

Assuming that evapotranspiration (ET) is the dominant component of water loss, followed by stream flow (runoff) on this humid, poorly drained coastal plain, the smallest watershed WS 80, with an average runoff ratio of 22%, might have lost almost 78% of the rainfall to ET. Similarly, the ET losses from the watersheds WS 79 and WS 78 were estimated to be 73% and 56%, respectively, of the total rainfall. The ET losses of 73% (993 mm on average) and 78% (1032 mm on average) of total rainfall of 6617 mm for the 5-year period for WS 79 and WS 80 are consistent with average annual estimated ET of about 1000 mm or more for the area (Young and Klaiwitter, 1968; Harder, 2004). Therefore, the 56% of rainfall lost as ET on WS 78 may have been possibly underestimated due to overestimation of stream flow.

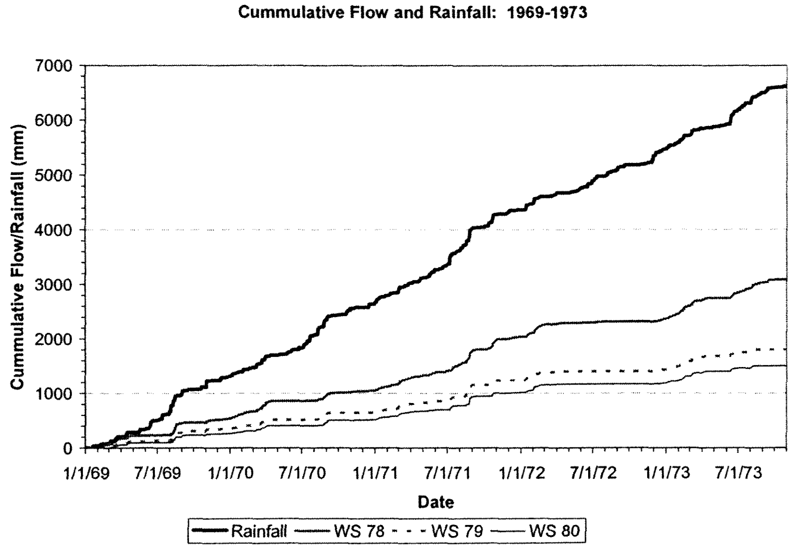


Figure 3. Daily cumulative rainfall and stream flows from three watersheds for 1969-73.

It can be generally argued that the annual stream flows from large watersheds may be somewhat higher for reasons such as large topographic gradient and base flows, and spatial heterogeneity in land use, soils and vegetation (Amatya et al., 2002). Especially, in the case of the watershed WS 78 (Turkey Creek), both the average gradient and base flows may be somewhat higher than that for both WS 79 and WS 80. Most importantly, this watershed has some parts of the land that are developed such as roads, buildings, agricultural lands and open areas, all of which contribute to higher runoff. A very large area of the watershed on poorly drained clayey soils especially on the right bank and at the headwaters also may contribute to larger runoff. Furthermore, unlike WS 79 and WS 80, which are both mature forests within the Santee Experimental Forest, some of the forested lands on the large watershed WS 78 within the Francis-Marion National Forest, may have been in various treatments such as thinning, burning, clear-cut and open lands. The other possible source of error may be in measured depth-based flows, which are dependent on the measured drainage area. The accurate measurement of drainage area on these flat lands like this is a challenging task. The problem may even more be exacerbated during large storm events when the water table is on the surface which may cause surface runoff across the watershed boundary.

## *Flow Duration Analysis*

Daily flow duration curves derived using measured daily depth-based stream flow data from all three watersheds (WS 78, WS 79 and WS 80) for the five-year (1969-73) period are presented in Fig. 4. A median plotting position was used to estimate the exceedance probability. The steeper slopes at the higher ends of the curves (for 1% of the time) for the watersheds WS 79 and WS 80 indicate their flashiness compared to the largest watershed WS 78. Apparently, the highest flows that occurred during this period were 85 mm on WS 79, 49 mm on both WS 78 and WS 80. Almost 0.9% of the time (16 out of 1765 days) the daily flow exceeded 15 mm with the watershed WS 79 yielding the highest followed by WS 80 and WS 78. The daily flow on the largest watershed WS 78 exceeded the flows on two other watersheds for nearly 98% of the time. That is one of the reasons the annual outflow from this watershed, as discussed earlier, was consistently higher than those for other two. The first-order watershed (WS 80) yielded flows only 60% of the time whereas the flows exceeded zero values 66% and about 80% of the time for the second- (WS 79) and third-order (WS 78) watersheds. This is generally expected because as the watershed size grows the stream flow occurs for extended period of time possibly due to increased base flows. The median (50-percentile) daily flows were 0.05 mm, 0.09 mm and 0.70 mm for WS 80, 79 and 78, respectively.

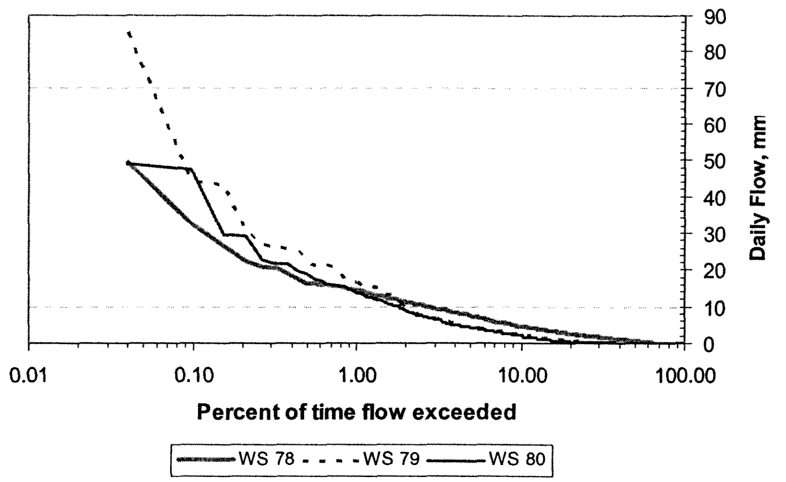


Figure 3. Daily flow duration curves for three watersheds for 1969-73.

### *Flood Frequency Analysis*

Results of calculations and analysis are presented in the following manner: first the maximum floods calculated using Pearson-III distribution for all three watersheds are presented in Table 1, 2 and 3. Next results of calculations using regional formulae are presented in Table 4 and finally the results of calculations using Gumbel distribution for minimum discharges are presented in Tables 5, 6 and 7. Interestingly, the 100-yr return period flood discharge of 1750 cfs computed for the design of current new bridge at Turkey Creek on Hwy 41N is between the1613 cfs computed by Pearson-III distribution (Table 1) and 1865 cfs the SC Regional formula (Table 4).

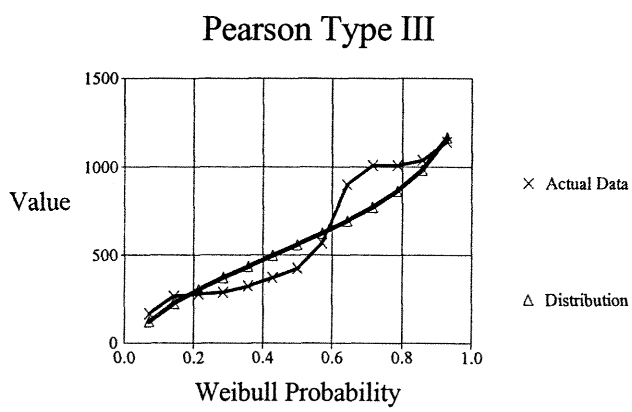


Figure 1. Maximum floods (cfs) for watershed WS 78 obtained using Pearson-III distribution.

Table 1. Maximum floods for watershed WS 78 obtained using Pearson-III distribution.

| Probability of flow | Return period (years) | Predicted flow value (cfs) | Standard error (cfs) |
|---|---|---|---|
| 0.995 | 200 | 1756 | 505 |
| 0.990 | 100 | 1613 | 418 |
| 0.980 | 50 | 1464 | 336 |
| 0.960 | 25 | 1307 | 261 |
| 0.900 | 10 | 1080 | 179 |
| 0.800 | 5 | 886 | 137 |
| 0.667 | 3 | 719 | 121 |
| 0.500 | 2 | 560 | 112 |

Table 2. Maximum floods for watershed WS 79 obtained using Pearson-III distribution.

| Probability of flow | Return period (years) | Predicted flow value (cfs) | Standard error (cfs) |
|---|---|---|---|
| 0.995 | 200 | 540 | 560 |
| 0.990 | 100 | 441 | 367 |
| 0.980 | 50 | 351 | 244 |
| 0.960 | 25 | 268 | 202 |
| 0.900 | 10 | 175 | 199 |
| 0.800 | 5 | 119 | 161 |
| 0.667 | 3 | 89 | 93 |
| 0.500 | 2 | 73 | 16 |

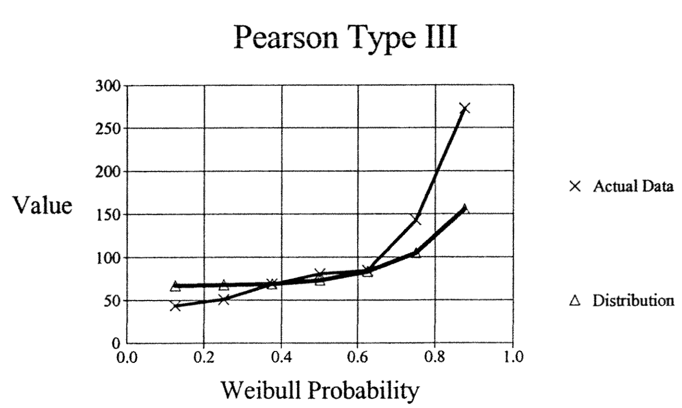


Figure 2. Maximum floods (cfs) for watershed WS 79 obtained using Pearson-III distribution.

Table 3. Maximum floods for watershed WS 80 obtained using Pearson-III distribution.

| Probability of flow | Return period (years) | Predicted flow value (cfs) | Standard error (cfs) |
|---|---|---|---|
| 0.995 | 200 | 81 | 30 |
| 0.990 | 100 | 73 | 24 |
| 0.980 | 50 | 65 | 18 |
| 0.960 | 25 | 57 | 13 |
| 0.900 | 10 | 46 | 8 |
| 0.800 | 5 | 38 | 6 |
| 0.667 | 3 | 31 | 5 |
| 0.500 | 2 | 24 | 5 |

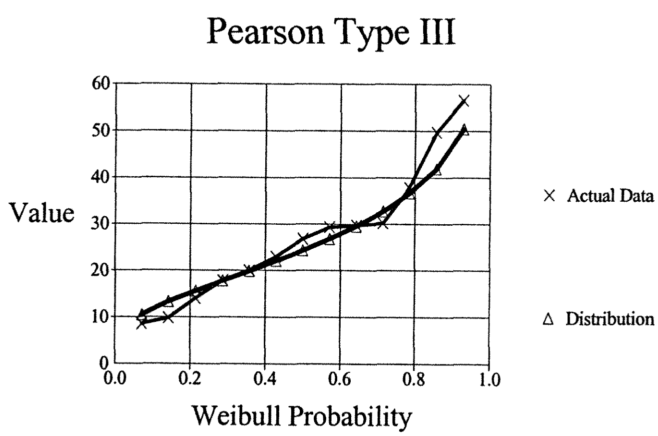


Figure 3. Maximum floods (cfs) for watershed WS 80 obtained using Pearson-III distribution.

Table. 4 Maximum floods for watersheds WS 78, WS 79 and WS 80 obtained using regional formulas for South Carolina, Lower Costal Plain, rural areas.

| Probability of flow | Return period (years) | Predicted flow value (cfs) WS78 | Predicted flow value (cfs) WS79 | Predicted flow value (cfs) WS80 |
|---|---|---|---|---|
| 0.999 | 500 | 2653 | 801 | 505 |
| 0.990 | 100 | 1865 | 491 | 293 |
| 0.980 | 50 | 1531 | 403 | 241 |
| 0.960 | 25 | 1268 | 326 | 194 |
| 0.900 | 10 | 900 | 231 | 137 |
| 0.800 | 5 | 675 | 166 | 97 |
| 0.500 | 2 | 418 | 85 | 49 |

Table 5. Minimum floods for watershed WS 78 obtained using Gumbel distribution.

| Probability of flow | Returned period (years) | Predicted flow value (cfs) | Standard error (cfs) |
|---|---|---|---|
| 0.995 | 200 | 1.36 | 0.43 |
| 0.990 | 100 | 1.22 | 0.38 |
| 0.980 | 50 | 1.08 | 0.32 |
| 0.960 | 25 | 0.93 | 0.26 |
| 0.900 | 10 | 0.74 | 0.18 |
| 0.800 | 5 | 0.59 | 0.12 |
| 0.667 | 3 | 0.47 | 0.08 |
| 0.500 | 2 | 0.36 | 0.05 |

Table 6. Minimum floods for watershed WS 79 obtained using Gumbel distribution.

| Probability of flow | Returned period (years) | Predicted flow value (cfs) | Standard error (cfs) |
|---|---|---|---|
| 0.995 | 200 | 1.04 | 0.19 |
| 0.990 | 100 | 0.94 | 0.17 |
| 0.980 | 50 | 0.85 | 0.15 |
| 0.960 | 25 | 0.76 | 0.12 |
| 0.900 | 10 | 0.63 | 0.08 |
| 0.800 | 5 | 0.54 | 0.06 |
| 0.667 | 3 | 0.46 | 0.05 |
| 0.500 | 2 | 0.39 | 0.03 |

Table 7. Minimum floods for watershed WS 80 obtained using Gumbel distribution.

| Probability of flow | Returned period (years) | Predicted flow value (cfs) | Standard error (cfs) |
|---|---|---|---|
| 0.995 | 200 | 0.73 | 0.13 |
| 0.990 | 100 | 0.67 | 0.12 |
| 0.980 | 50 | 0.60 | 0.10 |
| 0.960 | 25 | 0.54 | 0.08 |
| 0.900 | 10 | 0.46 | 0.06 |
| 0.800 | 5 | 0.39 | 0.04 |
| 0.667 | 3 | 0.34 | 0.03 |
| 0.500 | 2 | 0.29 | 0.02 |

## Summary and Conclusion

A study was conducted to examine the stream flow dynamics of three experimental forested watersheds (1st order, WS 80 – 200 ha; 2nd order, WS 79 – 500 ha; and 3rd order, WS 78 – 5000 ha) located at the Francis Marion National Forest in coastal South Carolina. Historical precipitation and stream flow (runoff) data measured during 1964 to 1976 before Hurricane Hugo (1989) were used to derive annual rainfall-runoff ratios, daily cumulative flows and flow duration curves, and flood frequency analysis for these watersheds. Results showed that the variability of annual runoff was much higher among watersheds than that for rainfall. Average annual computed runoff as a percentage of rainfall was the highest (44%) for the 3rd order watershed (WS 78) followed by the 2nd order watershed WS 79 (27%) and the 1st order watershed WS 80 (22%). The increase in runoff on WS 79 compared to WS 80 was possibly due to treatments on part of the WS 79. Although the land use and soils effects, ground water inputs, and variability in rainfall may have attributed to increased stream flows on the largest watershed (WS 78), its 100% increase in runoff (3082 mm) compared to 1506 mm on the smallest watershed (WS 80) for the five-year period may have also been due to, somewhat overestimate in flows. Although the annual runoff coefficients presented here may provide insight on average watershed response and stream flow dynamics, they may not sufficiently capture the dynamics of runoff generation processes in which case seasonal dynamics are recommended. Srinivasan et al. (2005) recently demonstrated a need of seasonal prediction of runoff dynamics for understanding the phosphorus transport process.

Flow duration data indicated some flashiness (higher peak flows) of the smaller watersheds compared to the largest watershed WS 78. The daily flows on WS 78 occurred for 80% or more time compared to only 66% and 60% for WS 79 and WS 80, respectively. Also, for about 98% of the time the daily flows on WS 78 were higher than those from two other watersheds. The median (50-percentile) daily flows were 0.05 mm, 0.09 mm and 0.70 mm for WS 80, WS 79, and WS 78, respectively. The flow frequency analysis with 13, 7 and 13 years of peak flows for WS78, WS79 and WS80, respectively, employing Pearson III-type distribution revealed the peak flows for 100-, 50-, 25-, 10-, and 5-year return periods as 1805, 1565, 1326, 1009, and 769 cfs for WS78, 379, 325, 272, 200, and 146 cfs for WS79, and 73, 63, 54, 41, and 32 cfs for WS80. These results are in good agreement with data calculated using USGS developed formulae for South Carolina Lower Coastal Plain.

Stream flow data currently being collected at the new USGS gauging site on Turkey Creek watershed (WS 78) and our continuing flow measurements on the watersheds WS 79 and WS 80 will provide insight about relationships of runoff-rainfall among these watersheds after the impacts of Hurricane Hugo. The historical data from the Turkey Creek watershed along with aerial photographs for successional years are also being used to evaluate the effects of land use change and the hydrologic effects of Hurricane Hugo in September 1989.

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